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THE GEOLOGY AND PETROLOGY OF THE TOOBORAC DISTRICT, VICTORIA

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Contents

Introduction

The district described in this paper covers an area ten miles by seven made up of the Parish of Tooborac and portions of the Parishes of Warrowitue, Panyule and Pyalong, all in County Dalhousie. Tooborac itself lies on the Kilmore-Bendigo railway some sixty miles north of Melbourne and ten miles south of Heathcote.

This area is a continuation to the south of the district surveyed by Thomas (23) and completes the mapping of the southern half of the Mt. William-Heathcote-Colbinabbin axis. The geological mapping was carried out by compass and pacing traverses, using as a basis the Military Survey maps (Pyalong and Heathcote Sheets) on a scale of one mile to the inch and Lands Department Parish Plans on scales of twenty and forty chains to the inch. The area between Tooborac and the Sugarloaf was surveyed by chain and compass traverses on a five-chain grid. Difficulty was expereinced in the detailed mapping of the Cambrian rocks through the paucity of good outcrops. Every exposure has been examined, but intervening areas are generally not amenable to detailed study.

Previous Work

Very little work has been carried out in this area in the past. The south-western corner is included in Quarter Sheet No. 51 S.W. of the

Geological Survey of Victoria, which was surveyed in 1856 by N. Taylor, who from the contact zone of the Cobaw granite in the vicinity of Hayes Hill recorded gneiss, now shown to be part of a metamorphosed porphyrite dyke. Dr. A. W. Howitt (13) noted the presence of the 'diabase' series at Tooborac and figured a section of 'actinolite rock' from there. Three short survey camps were held in 1938, 1939 and 1940 by students of the University of Melbourne, when reconnaissance work was carried out over a large part of the area. Occasional references have also been made in Mines Department publications to auriferous quartz reefs at the Sugarloaf and elsewhere.

While little has been published on Tooborac itself, the proximity of the classic localities of Heathcote and Lancefield on the same trend-line makes a short summary of work in these areas desirable. At Heathcote and in the parishes to the north early Geological Survey workers regarded the igneous rocks as trap dykes intruded along the boundary between the Lower (Ordovician) and Upper Silurian. Selwyn (18), Murray (17). In 1888 and 1891 E. J. Dunn (5) recorded both intrusive and extrusive rocks, with tuffs and jaspers. As a direct result of this the area was resurveyed by E. Lidgey and W. H. Ferguson, who considered that the diabases were conformable with the Lower Silurian while the Upper Silurian was deposited unconformably upon both series. Trilobite-bearing beds were discovered at the base of the Lower Silurian and were later shown by R. Etheridge (11) to be Cambrian in age. Howitt published a petrological report on the igneous rocks in 1896 (13) in which he maintained that the cherts were formed by the alteration of Lower Silurian shales during the intrusion of the diabases and granites, a view to which Lidgey then agreed.

In 1903 Professor J. W. Gregory (12) published a paper on the diabasic rocks of Victoria and concluded that both Ordovician and Silurian had been deposited unconformably upon the diabases and schistose rocks, for which he coined the term Heathcotian. He believed that the trilobite beds were Ordovician in age. This was confirmed by F. Chapman. Prof. E. W. Skeats (19) was of the opinion that the diabases were mainly effusive and probably Lower Ordovician in age. He also recorded the presence of *Protospongia* in the cherts which he regarded as altered Ordovician rocks. Chapman (3) in 1917 described collections from the trilobite beds and stated that the trilobites were Upper Cambrian in age, while some of the brachiopods were Ordovician in their affinities.

Recently Dr. D. E. Thomas has remapped the area and proved that the Cambrian rocks are separated from the Ordovician and Siluro-Devonian by high angle reverse faults. His work shows the structure to be extremely complex, with both strike and oblique faulting, and extensive shearing. He established a conformable sequence between the Middle Cambrian Dinesus-Hydroid beds and the Ordovician both at Knowsley East, north of Heathcote, and at Lancefield, and he also zoned the Silurian rocks and proved the presence of Yeringian (Lower Devonian) rocks.

At Lancefield, Skeats (20) showed that the Ordovician was deposited conformably on the Cambrian diabases and cherts, which he believed

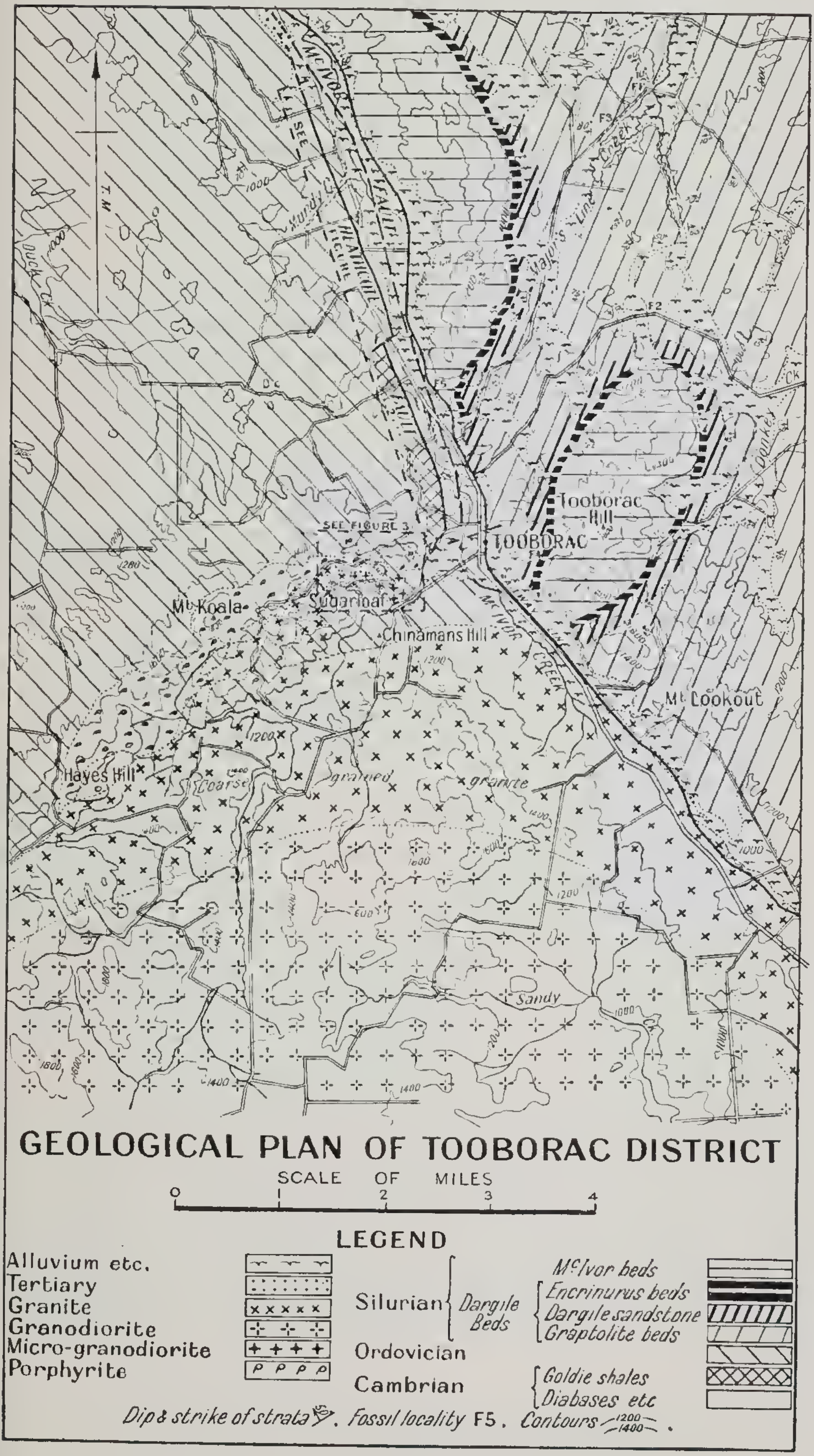
T.N.
McIVOR FAULT
HEATHCOTE FAULT
SEE FIGURE 3
Mundy Ck
Duck Ck
Majors Line Creek
Donkey Ck
F1
F2
F3
F5
Tooborac Hill
TOOBORAC
Mt Koala
Sugarloaf
Chinamans Hill
McIvor Creek
Mt Lookout
Hayes Hill
Coarse grained granite
Sandy Ck
1000
1200
1400
1600
1800
GEOLOGICAL PLAN OF TOOBORAC DISTRICT
SCALE OF MILES
0
1
2
3
4
LEGEND
Alluvium etc.
Tertiary
Granite
Granodiorite
Micro-granodiorite
Porphyrite
Silurian
Dargile Beds
McIvor beds
Encrinurus beds
Dargile sandstone
Graptolite beds
Ordovician
Cambrian
Goldie shales
Diabases etc
Dip & strike of strata
Fossil locality F5.
Contours 1200 1400

FIG. 1

to be marine. He thought that the Silurian was deposited unconformably upon the Cambrian with basal conglomerates. This area has been resurveyed by Thomas, who found that the Cambro-Silurian boundary is a high-angle reverse fault similar to those at Heathcote. The conglomerates were proved to be interbedded and to be conformably underlain by Upper Ordovician, and a conformable succession from the diabases through the Upper Cambrian Goldie Series to the Lower Ordovician was established.

General Geology

The oldest rocks exposed in the area are altered igneous and pyroclastic rocks of Cambrian age which outcrop along a narrow belt trending slightly west of north and forming part of a major structural feature of Central Victoria — the Mt. William-Heathcote-Colbinabbin Cambrian belt. This belt forms the western limit of Siluro-Devonian sedimentary rocks in Victoria and separates them from the main areas of Lower Ordovician to the west. The eastern boundary of the Cambrian belt is a reverse fault—the McIvor Fault—which brings Cambrian against the higher zones of the Silurian, involving a stratigraphic throw of tens of thousands of feet. The western boundary, the Heathcote Fault, is of much smaller dimensions, faulting Lower Ordovician against the Cambrian. As demonstrated by Thomas at Heathcote, these faults are high-angle reverse faults hading to the west.

The Cambrian rocks, especially the tuffs, have been sheared and reconstituted by low-grade dynamic metamorphism and metasomatism associated with the faulting. As a result the structure of the belt, which has been shown by Thomas to be strongly folded north of Heathcote, has been largely obliterated in the Tooborac area.

The Ordovician sediments to the west are closely folded, whereas the Silurian by comparison is simple in structure, being folded into broad open pitching folds. Two small strips of Ordovician slate have been faulted into the Cambrian, but the mechanism involved is difficult to picture.

This whole sequence has been intruded at the close of the Devonian by the Cobaw batholith, a compound intrusion of granite and granodiorite, with associated hypabyssal types including hypersthene porphyrite which has been metamorphosed by the granite. A series of diopside-bearing rocks occurs sporadically through the metamorphic aureole and is believed to be metasomatic in origin.

Post-Tertiary high-level gravels occur at the northern end of the area but are not traceable further south. Both these gravels and the alluvial deposits along the main streams are auriferous.

Physiography

Tooborac lies on the northern flanks of the Western Highlands Province of Victoria. The country is broadly undulating, with steep ridges of the more resistant rocks rising above the general level. The most important of these is the ridge of hornfels forming the metamorphic aureole of the Cobaw batholith, which is a complete ring broken only by narrow gaps through which pass the main streams draining the granite. In general, the granitic rocks occupy lower ground than the aureole, but are higher than the unaltered sediments to the north. The long ridge between Tooborac and Heathcote, and Tooborac Hill, are composed of hard Silurian sandstones and directly reflect its structure. Alluvial fans are conspicuous along the foot of these ridges.

The annual rainfall varies from 25 ins. to 30 ins., and the main streams rising within the area are intermittent and cease to flow during the summer months. They are mostly early mature streams with narrow flood plains. A high-level terrace is present along McIvor Creek, and at the northern end of the area Post-Tertiary gravels occur.

The control of the stream patterns by the geology is most marked. In the Ordovician the pattern is parallel to the strike of the interbedded sandstones and slates, while the softer Silurian mudstones give rise to an open dendritic type. In the granitic rocks the control exercised by jointing has resulted in a modified rectangular drainage pattern.

Cambrian

A succession of altered igneous and pyroclastic rocks belonging to the Heathcote Formation of pre-Middle Cambrian age outcrop along a narrow belt bounded on the east and west by the McIvor and Heathcote Faults respectively. This belt marks the crest of the Mt. William-Heathcote-Colbinabbin axis, being a southern extension of the Heathcote section between South Heathcote and the Cobaw granitic massif. Two distinct changes are evident in the trend of the Cambrian. At the northern end of the area, the north-westerly trend of the Heathcote section gives place to a north-northwesterly one, while about one mile north of the granite contact this in turn changes to a north-south trend on the same line as the meridional Mt. William section of the axis. No cross-faulting has been observed at either of these points, and the main boundary faults appear to be continuous, although slightly offset along a small tear fault on the fourth gully north of Tooborac.

The rocks are predominantly tuffaceous, with a number of small masses of albite-rich igneous rocks apparently intrusive into them. Presumed lava flows have been found in only two localities, while cherts, which are well-developed in other Cambrian areas of Victoria, and normal sediments are absent. This belt, therefore, is very similar lithologically to the Heathcote section, which is characterised by the predominance of pyroclastics and minor intrusives and differs from the Mt. William and Colbinabbin sections, which consist almost entirely of basic lavas interbedded with cherts, but with very few tuffaceous bands or minor intrusives.

The structure of the Cambrian belt is undoubtedly very complex, but the destruction of original stratification through the development of foliation and the scarcity of outcrops makes a detailed study of the structure impossible. The whole series has been extensively altered as a consequence of low-grade dynamic metamorphism and metasomatism, connected with the orogenic movements during the Devonian. Shearing and recrystallization under conditions of deep burial and moderate temperatures have resulted in the obliteration of many of the original structures and textures and in the complete reconstitution of the mineral assemblages. The tuffaceous rocks have developed a strong foliation, especially in the vicinity of the boundary faults, and have been metamorphosed to talc-chlorite and actinolite rocks. The igneous rocks have resisted the shearing movements better, but have been albitized and uralitized, and in some cases have been completely recrystallized. Metasomatic replacement has locally converted the pyroclastic rocks into jasperoids and calcareo-siliceous rocks.

As a result of this alteration, the identification of original petrological types has been made very difficult, so that only general terms can be used.

The Cambrian rocks also enter the metamorphic aureole of the Cobaw granite, which has metamorphosed the pyroclastics to tremolite hornfelses and the subordinate igneous rocks to epidiorite.

The Heathcote Formation (old 'Heathcotian') has been shown by Thomas (24) to be overlain in the Parish of Knowsley East by the *Dinesus*-Hydroid beds, a series of fine-grained sediments with interbedded ash beds containing the trilobites *Dinesus ida, Notasaphus fergusoni, Dorypyge* sp., *Agnostus* sp., and *Amphoton* sp. of Lower Middle Cambrian age—Whitehouse (28). The Heathcotian is, therefore, older than Middle Cambrian, but since its base is not known its lower age limit cannot be fixed.

PYROCLASTICS

Pyroclastic rocks form the greater proportion of the rocks of the Cambrian belt, and are mostly fine-grained, dynamically metamorphosed tuffs which, in places, have been altered metasomatically to jasperoids and calcareo-siliceous rocks. These tuffs have suffered considerably as a result of the shearing movements, which have produced a well-marked foliation, particularly evident in the vicinity of the boundary faults. They have been largely reconstituted during these movements and are now talc-chlorite and actinolite 'schists'.

The talc-chlorite type is well represented in the centre of the belt, where the rocks consist almost entirely of fine-grained talc and chlorite, with or without small amounts of quartz, iron ore, pyrite and calcite. In the coarser-grained rocks pseudomorphs of talc are common after primary ferromagnesian minerals, and the interstitial talc is itself rather coarser (6967, Pl. X, fig. 1). Any original stratification has been completely destroyed by the metamorphism and shear planes are abundant, being marked by films of limonite.

A representative section (6940) of the actinolitic type found in a small area to the northern end of the belt shows a very fine felt of pale green amphibole and actinolite fibres, with odd crystals of albite and fibrous actinolite.

Ash beds showing a similar development of pale green amphibole occur about two miles from the granite contact, but in this case the development of amphibole is believed to be due to incipient contact metamorphism, and these rocks are dealt with later.

In a number of scattered localities the tuffs have been altered metasomatically by silicifying solutions converting them into jasperoids and calcareo-siliceous rocks similar to those described by Skeats (20) from Heathcote. The jasperoids consist of fine cherty silica with small crystals of pyrite, patches of a green chloritic material—'selwynite'—and in one slide (6941) small clots of actinolite.

The calcareo-siliceous rocks are very similar but contain varying amounts of secondary carbonates (including siderite) and chlorite, in addition to the finely crystalline quartz.

These metasomatic rocks are more common at the northern end of the belt and are often found in close proximity to the boundary faults, which may have served as channels for the silicifying solutions. They are usually associated with the pyroclastics, from which they are apparently derived. The actual date of the metasomatism cannot be determined, but it is probably associated with the more general dynamic metamorphism. It is noteworthy that the northern outcrop contains many small quartz reefs which may possibly be related to the quartz reefs derived from the Devonian Cobaw granite.

LAVA FLOWS

Definite volcanic rocks have not been proved in this area, but at two small outcrops, C1, 2, the rocks are related petrologically to the basic lavas of the other Cambrian areas and may well be volcanic in origin. The junctions with the surrounding tuffs are not visible, and the rocks have been recrystallized, thus destroying original textures.

Outcrop C1 consists of a massive dark green rock showing small crystals of uralite, but no trace of flow structure or vesicles. Under the microscope (6942) it is finely porphyritic, with traces of the original phenocrysts, now altered to albite and green hornblende. The albite Ab_{91} contains saussurite and sericite, and shows partial replacement by micrographic quartz. Original ferromagnesian phenocrysts have been replaced by pale green uralitic hornblende, pale fibrous amphibole and chlorite which contain grains of secondary quartz and small clots of stilpnomelane. The groundmass has recrystallized to a fine-grained aggregate of albite, secondary hornblende and actinolite fibres, quartz, ilmenite and sphene.

The rock at locality C2 occurs as scattered boulders within green actinolitic tuffs and consists of fine-grained albite Ab_{98}, fibrous actinolite, fine granular quartz and odd nests of stilpnomelane (6943). The texture varies considerably, due to the effects of recrystallization. Albite occurs sometimes as well-formed twinned crystals, but more commonly in anhedral clots showing wavy extinction, while secondary quartz occurs in small veins and lenses. This rock has been largely recrystallized, so that its classification as a volcanic rock is not at all certain.

ALBITE-RICH ROCKS

A number of small masses of albite-rich rocks outcrop within the tuffs of the Cambrian belt and appear to be intrusive into them. The smaller ones are lenticular bodies only a few yards long, elongated in the general direction of the belt, and apparently parallel to the foliation of the surrounding tuffs. The larger masses, on the other hand, are more in the form of small bosses and appear to transgress the foliation

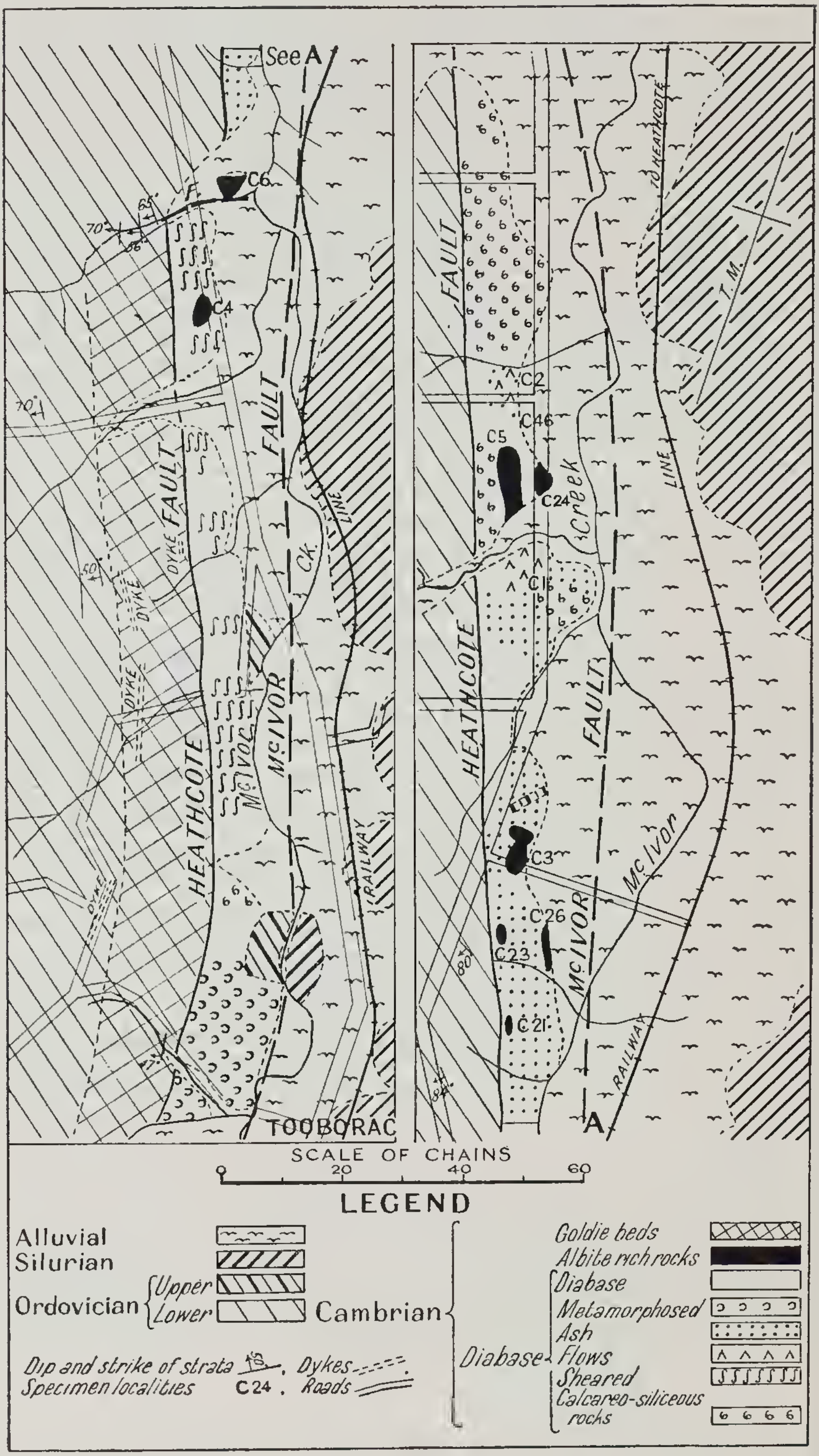

Fig. 2.—Detailed map of the area outlined in northern section of Fig. 1.

of the tuffs. This cannot be confirmed, however, because in no case has a junction with the tuffs been observed in the field.

Similar albitic rocks occur at Heathcote, where they are regarded as being intrusive into the tuffs. These rocks have been variously described as diorite, hornblende porphyrite and felspar porphyrite (Thomas (22)), but in all cases the felspar is apparently albite.

The albite-rich types are fine-grained massive rocks showing no traces of flow structure or original vesicles. Jointing is well developed in all outcrops, with individual joint planes from a few inches to several feet apart. As there is no evidence of movement along these planes, they are considered to be younger than the tectonic movements and probably due to relief of pressure through erosion of the overlying rocks and to expansion on weathering.

These rocks have not been directly affected by the shearing movements, although in one rock (6944) fine shear planes are detectable under the microscope. This may be explained by their greater competence causing them to behave under the shear stresses as small rigid augen enclosed by the incompetent pyroclastics.

All these rocks are characterised by the abundance of albite, which, in the less altered rocks at least, is the dominant constituent. Both porphyritic and equigranular types are present, but the subsequent recrystallization has destroyed the original textures in many of the rocks.

The outcrop of C4 is representative of the less altered porphyritic types. It is a light brown rock containing subhedral tabular phenocrysts of albite Ab_{95} up to 3 mm. long set in a microcrystalline groundmass of albite, clots of secondary stilpnomelane, accessory iron ore and odd needles of apatite (6945, Pl. X, fig. 4). The albite phenocrysts are quite fresh and show twinning on the Carlsbad, albite, and pericline laws, while the groundmass also shows no sign of recrystallization.

The larger body near the northern end of the belt is very similar to the above but shows greater variation in texture and degree of recrystallization. Slide 6946 of the least altered rock contains, in addition to the fresh albite phenocrysts, needles of brown hornblende which have been largely replaced by fibrous actinolite. The groundmass is rather coarser grained, consisting of albite, stilpnomelane and actinolite fibres, and granular sphene. Slide 6947 contains no amphibole, and the groundmass albite is partially recrystallized. Stilpnomelane and sphene are common and clots of secondary quartz and chlorite are present. In slide 6948 the groundmass has recrystallized to a quartz-albite intergrowth, and micrographic quartz has begun to invade some of the albite phenocrysts. Secondary stilpnomelane, calcite and chlorite are present, while the albite phenocrysts contain small grains of clinozoisite.

The rock at C24 (6949) is closely allied but contains less stilpnomelane, so that it is lighter grey in the hand specimen. The albite phenocrysts contain clinozoisite grains, but the groundmass albite has not recrystallized.

The same course of alteration is shown by the small body at C6, which consists of two outcrops about one chain apart, the interval between being covered by a thin veneer of alluvium. While the textures of the two outcrops differ, it is apparent that they belong to the same body, and this is supported by the occurrence in both of prismatic brown hornblende showing progressive replacement by secondary green amphibole, colourless epidote and chlorite. This brown hornblende has been found in only one other rock, 6946, described above.

The least altered rock from the northern outcrop, 6950, is similar to the small body in allotment 16, Parish of Heathcote, which has been described erroneously by Howitt (13) as labradorite porphyrite. The plagioclase felspar in both rocks is albite, not labradorite. The Tooborac rock is fine porphyritic grey-green rock containing phenocrysts of euhedral to subhedral brown hornblende up to 3 mm. long and saussurite in a fine groundmass of albite, quartz, chlorite, saussurite, leucoxenized ilmenite and odd pyrite grains. The hornblende is quite fresh but is often corroded and contains grains of iron ore, while the groundmass also shows no sign of recrystallization.

Slide 6951, also from the northern outcrop, shows an intermediate stage of alteration. The albite Ab_{92} is clouded and partially replaced by clinozoisite and sericite, while the brown hornblende is largely altered to fibrous green amphibole. Rather more granular quartz is present in the coarser grained groundmass, which also contains some clinozoisite, calcite and apatite.

The southern outcrop is more coarsely granular, and in this section (6952) is seen to be more equigranular and to consist of albite crystals Ab_{92} largely replaced by micrographic quartz and relics of brown hornblende altering to fibrous green amphibole and aggregates of colourless epidote, clinozoisite and chlorite. Accessories include leucoxenized ilmenite, sphene and apatite.

The rock at C3 (6953) belongs to the group of rocks containing no ferromagnesian minerals. It is a fine-grained, greenish-grey rock consisting of clouded albite crystals Ab_{92} in a groundmass which has recrystallized to quartz-albite intergrowths frequently radiating from a central albite crystal. Quartz crystals are not common but may be primary. The albite contains grains of clinozoisite and sericite, while secondary calcite, chlorite and sphene are common in the groundmass.

The rock at C25 (6954) consists predominantly of fine granular albite Ab_{93} with small amounts of quartz, chlorite, calcite, apatite, and limonite after pyrite. This rock is the only example of the massive rocks in which shear planes can be identified with certainty. These are distinguished by a very thin zone of granulation in which calcite, chlorite and pyrite have been occasionally introduced.

A boulder at the southern end of this outcrop is more altered and consists of albite containing clinozoisite in a base of granular quartz, quartz-albite intergrowth, aggregates of clinozoisite, ilmenite, sphene and chlorite (6955, Pl. X, fig. 3). This rock contains a light-coloured vein of quartz, albite, clinozoisite and radial quartz-albite intergrowths.

Rocks 6957, 6958 and 6959 are related to 6949 but are very fine-grained. They contain microphenocrysts of lath-shaped twinned albite in an aphanitic base of quartz, albite and a little secondary amphibole. In 6959 the albite laths show a slight preferred orientation.

In rock 6960 the albite base has recrystallized as radiating aggregates with wavy extinction containing fine granular quartz and odd albite laths.

Rock 6961 is a fine-grained grey rock composed of albite laths Ab_{90} and small quartz grains, with an interstitial groundmass of albite, secondary calcite, and chlorite.

In certain rocks stilpnomelane becomes the dominant mineral to such an extent that the original nature of the rock is uncertain. In rock 6962 it occurs as a mesh of fine needles and plates, together with quartz, albite showing wavy extinction, and odd fibres of actinolite. A veinlet crossing this slide is composed entirely of stilpnomelane and small amounts of vein quartz.

Rock 6963 (Pl. XI, fig. 1) is a brown micaceous rock composed of clots and plates of fairly well formed stilpnomelane in a base of cherty silica, and is more probably an altered ashbed.

Even in the less altered igneous rocks the felspars have been albitized but still retain their original subhedral to euhedral form. They often contain some saussurite which, on further alteration, aggregates into small grains of clinozoisite. In the more intensely altered rocks the albite, as well as containing grains of clinozoisite, shows progressive replacement by introduced micrographic quartz, while the groundmass albite has also recrystallized again with the introduction of micrographic quartz.

Quartz when present is usually secondary, occurring either as small anhedral grains, as vein quartz, or intergrown with and replacing albite. In some of the albitic intrusives the larger clear quartz crystals may possibly be primary.

Prismatic brown hornblende has been found in only two localities and in each case (6946, 6952) shows progressive replacement by a number of secondary minerals, including pale-green amphibole, actinolite, chlorite and colourless epidote. This, together with its occurrence as euhedral crystals in slide 6946, supports the view that the brown hornblende is a primary mineral. The green amphibole of 6942 is definitely secondary, probably replacing a primary pyroxene.

Primary ilmenite shows alteration first to leucoxene, followed by recrystallization to granular sphene.

The characteristic secondary ferromagnesian mineral is a pale yellow-green fibrous amphibole with a small extinction angle up to 5°, being often associated with fine needles of actinolite, to which it is probably related. Its polarization colours are somewhat anomalous, which is apparently caused by partial chloritization of the amphibole.

Another commonly occurring secondary mineral is a yellow-brown micaceous mineral which occurs as sheaf-like aggregates and amorphous clots and agrees optically with stilpnomelane—Hutton (14). It is strongly pleochroic (X golden-yellow, Y, Z reddish-brown, $X < Y = Z$), pseudo-uniaxial negative, refractive indices ($X = 1{\cdot}598$, $Z = 1{\cdot}690$) and it extinguishes parallel to the basal cleavage, in which position the mottled effect characteristic of biotite is absent.

Members of the epidote group are common in the more altered igneous rocks. In all cases where the grain size permits they have been determined as clinozoisite, but odd colourless grains associated with the altered brown hornblende show higher birefringence, suggesting a slightly ferriferous variety. In a few rocks (6952, 6955, Pl. X, fig. 3) clinozoisite forms quite large radiating aggregates, sometimes showing spectacular deep blue interference colours.

The general abundance of albite suggests that the series belongs to the spilitic suite, and there arises the question of time and cause of albitization. In the majority of the igneous rocks the albite is accompanied by other signs of alteration, either partial alteration of primary brown hornblende or introduction of secondary minerals, notably stilpnomelane, normally indicative of low grade metamorphism. This, together with the association of the albite-rich rocks with foliated tuffs, would suggest that albitization is connected in part at least with the dynamic metamorphism. Such an occurrence has been described by Hutton (14) from the Otago schists of New Zealand, where dynamically metamorphosed basic igneous rocks belonging to the chlorite zone have given rise to mineral assemblages similar to those described herein.

Unfortunately the evidence available from the Tooborac rocks is inconclusive and solution of this problem must await a complete petrological study of all the Cambrian igneous rocks of Victoria. It is suggested, however, that albitization was caused by metasomatic replacement associated with the dynamic metamorphism and that the albite is therefore neither primary nor of deuteric origin. Eskola *et al.* (10) have proved experimentally that, under high pressures and at moderately elevated temperatures (200°-550° C.) and in the presence of soda-rich solutions, basic plagioclases do become albitized. Such conditions may well have been present in deeply buried geosynclinal deposits such as those in the Victorian Lower Palaeozoic. The soda-rich solutions would be derived from sodium salts entrapped during deposition of the overlying sedimentary rocks.

Owing to the subsequent alteration, the original composition of the igneous rocks, especially the intrusives, is very difficult to determine by direct means. It is definite, however, taking into account the basic lavas of the Mt. William and Colbinabbin Ranges, that the Cambrian igneous rocks belonged to a basaltic suite. On this basis, the Tooborac volcanic rocks are probably altered basalts, while the albite intrusives may represent the more acidic differentiates, possibly of original trachytic composition.

CONTACT METAMORPHOSED CAMBRIAN ROCKS

The Cambrian rocks outcrop within the metamorphic aureole of the Cobaw granite but, owing to faulting, are not present in the immediate contact zone. The metamorphosed rocks are found in a small area on McIvor Creek directly west of Tooborac, where, together with hornfelses derived from shales immediately to the west again, they form a mass of high-grade rocks isolated from the main belt of hornfelses. To the south, between these rocks and the granite, relations are obscured by an alluvial flat, while the inner contact zone is occupied by lower grade sericitic hornfelses probably derived from Ordovician rocks. To the west of the Cambrian the metamorphic grade again falls off so that it appears likely that granitic rocks are present at no great depth below the Cambrian.

As in the unmetamorphosed rocks, pyroclastics predominate, having been altered to massive tremolite hornfelses, while the subordinate igneous rocks have been metamorphosed to epidiorite. Certain tremolitic hornfelses with a base of fine-grained quartz apparently represent the nearest approach to cherts found in the area. Outcrops are very limited, thus obscuring the field relations of the different rock types and making the study of progressive metamorphism difficult.

PYROCLASTICS

Metamorphism becomes manifest about two miles north of the granite, where the tuffs are green foliated schists showing a strong development of actinolite needles and pale green amphibole. In thin section they contain small lenticles of cherty quartz and actinolite fibres surrounded by a felt of pale green amphibole and actinolite with scattered crystals of albite. These small lenticles represent fine cherty augen formed during the shearing movements.

As the contact is approached the pale amphibole becomes replaced by fine needles of tremolite which also enter the cherty lenticles and albite crystals, with the result that the schistose texture becomes obliterated. Pseudomorphs of original ferromagnesian minerals also consist of fibrous tremolite-actinolite. The highest grade rocks, apparently corresponding to the cordierite zone of the shales to the west, are non-foliated greenish hornfelses consisting almost entirely of interlocking fibrous tremolite with scattered iron ore grains and rounded blebs of quartz or albite Ab_{90-95}. The quartz blebs often consist of a single clear crystal showing partial replacement by tremolite needles encroaching from the margins (6964, Pl. XI, fig. 2). Some of these quartz crystals contain small euhedral crystals of zoned, untwinned oligoclase and also vermicular chlorite.

Associated with the tremolite hornfelses are rocks consisting of fine recrystallized quartz with coarser veins and clots of the same mineral, radial aggregates of tremolite-actinolite, and grains of iron ore. These siliceous rocks are thought to represent a small mass of metamorphosed cherts, the only occurrence of cherts in the area.

METAMORPHOSED IGNEOUS ROCKS

Odd boulders among these hornfelses are apparently metamorphosed igneous rocks. An example, 6965, is a fine-grained green rock composed of albite, fibrous green hornblende associated with small plates of biotite, and subordinate quartz and iron ore. Similar rocks from Mt. William classed as 'epidiorite' are metamorphosed basic lavas, and this rock is therefore grouped with them. The rocks of the other boulders consist of prismatic albite, fibrous tremolite-actinolite, quartz and iron ore, and, while definitely igneous in origin, little more can be deduced from them.

Ordovician

The rocks to the west of the Cambrian belt are closely folded sandstones, shales and slates with predominating westerly dips, so that higher horizons appear in that direction and form the eastern limb of a 'brachysynclinorium' centred around Redesdale and Baynton about ten miles to the west (Thomas (26)).

Abutting against the Heathcote Fault is a belt of unfossiliferous argillaceous rocks which are succeeded to the west by a thick sequence of argillaceous sandstones belonging to the Lancefieldian stage of the Lower Ordovician. At the western edge of the area these in turn are overlain by the normal Ordovician succession of interbedded sandstones, shales and slates.

An abrupt change of facies occurs within the belt of argillaceous rocks just north of the fourth gully from Tooborac. To the north of this gully the rocks consist of normal westerly dipping shales and arenaceous shales similar to those found throughout the Victorian Lower Ordovician. This formation can be traced northwards to Heathcote, where Thomas (25) believes them to be sheared Ordovician sandstones. In the parish of Tooborac, however, there is no evidence to justify this view for, although shearing has occurred in the immediate neighbourhood of the fault plane and slaty cleavage is strongly developed in the finer-grained rocks, the bedding of the rocks is clearly defined and shows no sign of disruption.

The strike of these shales is slightly oblique to the Heathcote Fault, thus exposing older beds towards the northern end of the area. The relation of the shales to the overlying sandstones appears to be a strictly conformable one.

To the south of the fourth gully the rocks are thinly bedded unfossiliferous shales and cherty shales about 1,000 ft. in thickness and having a high westerly dip with little or no minor folding. As with the northern shales there is apparently no discordance between these beds and the sandstones to the west. In weathered outcrops they have been altered by secondary silicification to light-coloured cherts. Along McIvor Creek they have also suffered contact metamorphism to tremolite-biotite-cordierite hornfels, a rock type not hitherto recorded from any Victorian contact zone in Ordovician rocks. This feature suggests original chemical differences between these rocks and the normal Ordovician shales, which may be due to the presence in the former of a proportion of pyroclastic material.

This formation is very similar lithologically to the unfossiliferous cherts and shales of the Upper Cambrian Goldie Series at Lancefield. However, in the absence of fossil evidence, any such correlation is very dubious. An alternative view is that it represents a higher horizon in the Lancefield stage of the Lower Ordovician, where cherty rocks are known to exist (personal communication from Dr. Thomas).

The change of facies at the fourth gully, which occurs significantly at the tear fault offsetting the Cambrian belt, seems to be too abrupt to be caused simply by lateral variation in facies. It therefore appears probable that the two formations are not equivalent, in which case the southern cherty shales, doubtfully correlated with the Goldie Series, must be separated from the normal Ordovician rocks to the west by a bedded fault which would pass undetected during any surface survey.

On fossil evidence collected by Thomas (23) at Heathcote both the shales north of the break and the overlying sandstones may be correlated with portion of the Lancefieldian stage at the base of the Lower Ordovician.

The two thin strips of black slates faulted into the Cambrian belt may be Upper Ordovician in age, by analogy with similar occurrences at Heathcote and Mt. Camel. However, they are very badly sheared and silicified, and as no graptolites have been found in them their age remains in doubt.

METAMORPHOSED ORDOVICIAN

Cordierite hornfelses derived from the metamorphosed Ordovician argillaceous sandstones constitute the greater part of the aureole of the Cobaw granite to the south-west of Tooborac and form a typical example of the normal contact alteration of argillaceous rocks such as has been described in Victorian rocks by Tattam (22) and Edwards and Baker (9). The hornfelses derived from the formation of cherty shales have not been previously recorded from Victoria and will be dealt with separately.

METAMORPHOSED SHALES

These rocks outcrop immediately to the west of the Cambrian tremolite hornfelses described above. As with the Cambrian rocks, they are not found in the inner contact zone, and the highest grade is developed immediately west of Tooborac near McIvor Creek.

The unaltered sediments are very fine-grained aggregates of sericite, a pale brown mica, and smaller amounts of quartz and iron ore dust. The cherty rocks consist of very fine-grained quartz with a little dusty iron ore but no sericite. Carbonaceous matter may be present in both types.

The sericitic rocks have been metamorphosed to biotite-pinite hornfelses in which the poikiloblastic cordierite has been subsequently altered to pale yellow pinite and flakes of sericite. The remaining minerals are quartz, sericite, fine biotite and iron ore.

The cherty shales first develop needles of tremolite or green hornblende, the groundmass remaining very fine-grained but with the addition of incipient crystals of pale brown biotite and pyrite. In a later stage, cordierite appears as poikiloblasts together with fine-grained biotite. Quartz is still fine-grained, while the tremolite needles have grown in size. The highest grade rocks consist of pools of poikiloblastic cordierite, clots of fine-grained brown biotite and radial groups of tremolite needles with a little quartz and pyrite (6966). The amphibole in these rocks belongs to the tremolite group and is a colourless prismatic mineral showing a typical amphibole cross-section, refractive indices ($X = 1{\cdot}629$, $Y = 1{\cdot}646$, $Z = 1{\cdot}654$), and a very low extinction angle except in sections perpendicular to Y which extinguish at up to 13°.

METAMOPHOSED ARGILLACEOUS SANDSTONE

The rocks of the sandstone belt are predominantly argillaceous sandstones consisting of grains of quartz, with lesser amounts of orthoclase, plagioclase-oligoclase Ab_{75} and andesine Ab_{65-70}, biotite, and white mica, in a matrix of fine quartz, chlorite, sericitic material, dusty iron ore, and detrital apatite, zircon and tourmaline. Small fragments of reef quartz and chert are rarely present. The finer-grained argillaceous rocks consist of varying proportions of quartz, chlorite, sericite and iron ore.

Initial Stage of Alteration. The course of metamorphism is the same in each case and the final products are distinguished only by the proportion of quartz present. The first signs of alteration are induration of the sediments and increase in the amount of secondary sericite and a pale green mica, which tend to segregate into rounded patches appearing as spots in the hand specimen. Small fibrous crystals of pale green fibrous chlorite are also present. With further recrystallization the white mica flakes increase in size and become the dominant constituent, while the remainder of the rock is made up of chlorite, quartz, iron ore, and a pale yellow mica which is apparently the first stage in the development of biotite.

Stage of Biotite Development. Nearer to the contact, biotite appears as small yellow-brown plates scattered among the flakes of white mica. It increases in size towards the contact and quickly assumes the dark red-brown colour characteristic of hornfelses. Quartz shows little change and is still strained, while original orthoclase is present and unaltered. The iron occurs as small grains often as centres for the formation of biotite.

Stage of Cordierite Development. The entry of cordierite into the hornfelses marks the complete reconstitution of the sediments. The cordierite hornfelses are dense bluish rocks which usually, but not always, occur close to a visible contact with granitic rocks. Bedding is still evident in weathered boulders which occasionally show ptygmatic folding, proving that these cordierite hornfelses were plastic during their formation. Cordierite first appears as poikiloblastic pools containing numerous small inclusions of quartz, biotite, and iron ore dust. In the highest grade rocks it becomes clear and granoblastic, with occasional six-fold twinning, but it is usually partly altered to a yellow isotropic material. In some rocks cordierite has altered retrogressively to pale green pinite. Besides cordierite, these hornfelses contain abundant quartz, biotite, muscovite, alkali felspar, rare oligoclase, and accessory iron ore, apatite, zircon, and brown tourmaline. Quartz has recrystallized and shows no strain effects. Very fine-grained alkali felspar occurs in the high-grade cordierite hornfelses and is characterised by the presence of exceedingly fine exsolution lamellae. In the lower grade rocks, corroded orthoclase is present but is soon completely resorbed, while crystals of oligoclase are rarely seen. The iron ore occurs as scattered grains, and some sections contain occasional grains of pyrite and native copper.

Granitized Hornfels. At a few places along the contact granitic material has been introduced into the cordierite hornfels as irregular veins of quartz, perthite, andesine Ab_{65} and biotite, which penetrate and merge into the surrounding hornfels (Pl. XII, fig. 2). Small porphyroblasts of quartz and perthitic orthoclase have also developed within the hornfels in the vicinity of these veins.

Quartzites. By increase in the amount of quartz the hornfelses may approach quartzites in composition when the rocks consist of a mosaic of interlocking quartz crystals with interstitial biotite and cordierite. One section from the junction of siliceous hornfels and an aplite vein shows the introduction of perthitic orthoclase and altered tourmaline between the quartz grains.

The hornfelses are all of the free-silica, non-calcic type, and, as indicated by the high sericite content of the unaltered sediments, are relatively high in potash. This would account for the presence of muscovite and, more especially, orthoclase in the cordierite rocks. As shown by Tilley (27), potash felspar may occur in the highest grades, being derived at the expense of biotite during the formation of cordierite.

The possibility of orthoclase being introduced from the granite magma must not be overlooked. Where this has definitely happened, orthoclase is porphyroblastic and is accompanied by the introduction of plagioclase, biotite, and quartz as well. However, in these hornfelses the orthoclase is very fine-grained and plagioclase is virtually absent, which would suggest that the orthoclase has formed from materials originally present in the sediments and not introduced from the granite.

Silurian

To the east of the Cambrian belt the sedimentary rocks are sandstones and mudstones of Silurian age, rather more openly folded than the Ordovician rocks to the west. They differ lithologically from the Ordovician, the arenaceous rocks being massive sandstones and quartzites, often devoid of bedding, and the argillaceous members thinly-bedded grey mudstones showing no fissility or development of slaty cleavage.

The Silurian sequence is divisible lithologically into an upper division of dominantly arenaceous facies which forms the southern end of the Heathcote Ranges and Tooborac Hill, and a lower, largely argillaceous division outcropping in the more open ground to the north and east. These mudstones contain thin sandstone horizons which grade vertically into mudstones and are too indefinite to be mapped in the field.

The structure of the Silurian is relatively simple and is admirably shown by the upper sandstones. The outcrop of the Heathcote Range forms the steeply-dipping westerly limb of a southerly pitching anticline, the nose of which has been cut off by the McIvor Fault. To the east of this anticline the sandstones reappear in the ridge of Tooborac Hill, where they have been folded into a synclinal structure having a high southerly pitch in the north and a low northerly one near the granite contact. The structure of the underlying mudstones is complicated by the presence of minor drag folds which in the north-east corner of the area obscure the main structures.

The Silurian rocks have been traced into the Parish of Heathcote, where they link up with the stratigraphical succession deduced by Thomas (25). Of Thomas's major subdivisions only the middle two—the Dargile and McIvor Groups—outcrop in the Tooborac district, but within these all his subdivisions have been recognized, as follows:

Division	Subdivision	Thickness
McIvor Group	3. Upper *'Camarotoechia'* Beds	5,000 ft. approx.
	2. Pelecypod Band	
	1. Lower *'Camarotoechia'* Beds	
Dargile Group	4. *Encrinurus* Mudstone	6,000 ft. approx.
	3. Dargile Sandstone	
	2. Graptolite Mudstones	
	1. Lower Dargile Mudstones	

DARGILE GROUP

The oldest exposed beds, a series of thinly-bedded unfossiliferous mudstones and intercalated sandstones, outcrop in the north-east corner of the area and may be correlated with Thomas's Lower Dargile Mudstones. These are overlain by a sandstone horizon containing starfish, small crinoids, and indeterminate brachiopods at locality F3, which in turn grades up into thinly-bedded grey mudstones with subordinate sandstone bands. In the Parish of Heathcote Thomas has found two graptolite horizons within these mudstones belonging to the zone of *Monograptus nilssoni,* but as yet only *M. bohemicus* has been collected from this horizon at Tooborac—F2. The graptolite mudstones also contain shelly fossils including *Palaeoneilo* sp., *Nucula* sp., *Bellerophon* sp., and *Dalmanites* sp. from locality F1. The thickness of all these mudstones is about 5,000 ft., making the thickness of the Dargile Group about 6,000 ft.

At the top of the graptolite beds the rocks become arenaceous and grade upwards into the Dargile Sandstone, a prominent horizon of fine-grained sandstones and quartzites about 700 ft. thick. It is poorly fossiliferous and at Tooborac has yielded only a few indeterminate brachiopods and crinoid ossicles at locality F4. The topmost hundred feet of the Dargile Sandstone is a massive quartzite which is useful as a marker bed and is abruptly overlain by the *Encrinurus* Mudstone, 400 ft. in thickness, containing *Chonetes* cf. *melbournensis* and *Encrinurus* sp. The *Encrinurus* Mudstone is very rarely exposed, being usually obscured by hillwash from the overlying sandstones. As a result the boundaries of this formation on the geological map are somewhat generalized.

The Dargile Sandstone heralds the change to an arenaceous facies which is represented at Tooborac by the McIvor Group.

McIVOR GROUP

The McIvor Group of massive sandstones and quartzites, about 5,000 ft. in thickness, is richly fossiliferous and is characterised by the abundance of *'Camarotoechia'* spp. (The generic position of these brachiopods is still uncertain.) The three-fold subdivision into lower *'Camarotoechia'* beds, a median pelecypod band, and upper *'Camarotoechia'* beds recognized by Thomas is readily apparent in the field, but was found impracticable to map. The species of *'Camarotoechia'* in the upper beds is larger than that in the lower beds and has fewer plications. The median pelecypod band is a massive blue quartzite well-exposed in some of the railway cuttings (F5) north of Tooborac, where it contains *Grammysia cruciformis, Leptodomus heathcotiensis* and indeterminate gasteropods. The McIvor Group is the youngest horizon occurring in the Tooborac district and members of the Mt. Ida Group of Yeringian age are not represented.

Owing to the paucity of detailed palaeontological work on the Victorian Siluro-Devonian faunas, exact stratigraphic correlation with other sequences is not possible. However, the graptolite beds of the Dargile Group can definitely be correlated with the Melbournian Stage (Lower Ludlow) and the Mt. Ida Group overlying the McIvor Group and containing *Pleurodictyum megastomum* and spiriferids allied to *Spirifer lilydalensis* with the Yeringian Stage (Lower Devonian). It therefore appears that the Tooborac Silurian succession covers the greater part of the Upper Silurian.

The contact between Silurian and granite is obscured by alluvial fans at the foot of Tooborac Hill, and the metamorphic rocks which are exposed are quartzites derived from the very pure sandstones of the McIvor Group.

Granitic Rocks

The country to the south between Tooborac and Mt. William is occupied by the Cobaw granitic massif, an oval-shaped body about 200 square miles in area. It is a compound batholith of the high-level discordant type characteristic of the epi-Devonian intrusions of Central Victoria.

At least two major phases are present, with less important hypabyssal modifications occurring outside the main intrusion between Tooborac and Hayes Hill. The core of the batholith is a medium-grained granodiorite closely resembling the Harcourt rock, surrounded by a younger annular intrusion of coarser-grained granite up to two miles in width. This granite is characterised by the presence of tabular orthoclase perthite crystals which are oriented in vertical flow layers parallel to the boundaries of the ring intrusion. G. Baker (2) has recorded this rock from Baynton, Pyalong, Mt. William and Big Hill, Lancefield, all on the periphery of the batholith, and it also occurs near the western margin at Kyneton and Sutton Grange.

The hypabyssal rocks outcrop as a series of dykes and apophyses in the 'fracture-zone' within the metamorphic aureole of the main intrusion. The oldest and most important of these is an arcuate dyke of hypersthene porphyrite four miles long and up to three-quarters of a mile wide, with associated smaller apophyses. This rock is very similar petrologically to some members of the hypersthene dacite suite of Central Victoria, notably the hypersthene dacite of Mt. Macedon, twenty-four miles to the south-west—Skeats and Summers (21). It is noteworthy that this is the first recorded occurrence of a member of this suite forming an intrusive body of any size.

Parallel to the hypersthene porphyrite and between it and the granite contact is a smaller dyke of medium-grained granite which at its western end grades imperceptibly into the coarse granite and in the east invades an older body of micro-granodiorite. Scattered throughout this complex are small dykes, apophyses and veins of quartz diorite, aplite, and pegmatite. Meridional porphyry dykes occur in the Ordovician, especially to the west near Baynton, and quartz reefs are common both in the metamorphic aureole and in the basement rocks to the north. These quartz reefs are the source rocks of the alluvial gold of the old Heathcote goldfield.

The outer contact of the batholith is very sharp and even. The country rocks are normally quite undisturbed right up to the contact and, except in the 'fracture-zone', are free from veining by the granite.

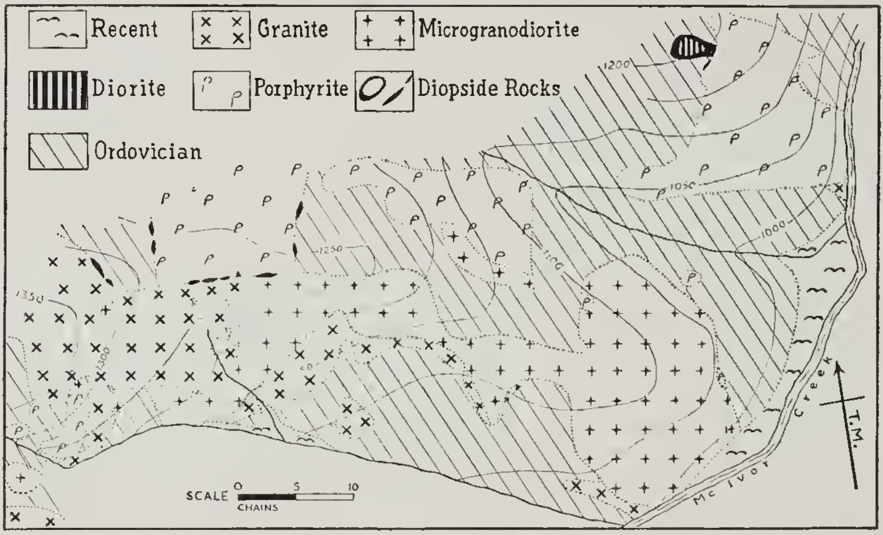

FIG. 3.—Geological map of the area between McIvor Creek and the Sugarloaf.

As mentioned above, some of the cordierite hornfelses show slight ptygmatic folding due to the softening of the rock during their recrystallization. In the 'fracture-zone' the sediments have been veined by medium-grained granite intruding along bedding and joint planes. This is particularly noticeable at Chinaman's Hill, where the network of veins resembles a stockwerk. By contrast the granite itself is remarkably free from inclusions of country rock, whereas the granodiorite forming the core of the intrusion contains numerous reconstituted xenoliths. This lends support to the view that the granodiorite is the older rock.

The inner contact between granite and granodiorite is also remarkably regular. The absence of veins and inclusions of one rock in the other has made the determination of their relative ages difficult. However, there is a gradational zone between the two types which may be up to ten feet wide. In this zone the orthoclase crystals are seen to grow in size towards the granite but are not oriented as are those in the granite.

This suggests that they have grown in place in the granodiorite from material supplied by the granite magma. Hence the granite is thought to have been intruded along the outer edge of the granodiorite soon after the latter had consolidated, but before the development of jointing.

Of the dyke rocks the hypersthene porphyrites are the oldest, having been intruded by both granite and microgranodiorite. The microgranodiorite has also been extensively veined by medium-grained granite, but evidence of the relative age of it and the granodiorite is unfortunately lacking. The sequence of intrusion therefore appears to have been:

5. Aplite, etc.
4. Granite.
3. Granodiorite.
2. Microgranodiorite.
1. Hypersthene Porphyrite.

This follows the normal trend towards increased acidity with the usual variations between felsic and mafic constituents shown very well by micrometric analyses and heavy mineral indices.

MICROMETRIC ANALYSES

Mineral	Microgranodiorite	Granodiorite	Coarse Granite	Medium Granite
Quartz	15·5	30·5	42·3	42·8
Orthoclase	10·5	25·8	31·8	34·1
Plagioclase	50·9	34·1	17·6	17·8
Biotite	19·9	8·6	6·6	3·7
Muscovite	—	—	—	—
Hornblende	3·3	·7	—	—
Garnet	—	—	—	1·5
Accessories	·1	·3	·3	—
Heavy Mineral Index	14·8	12·1	8·5	6·0

HYPERSTHENE PORPHYRITE

The intrusion of the hypersthene porphyrite dykes marked the first episode in the irruptive cycle. The main dyke was apparently intruded along a fracture developed in the roof of the rising magma chamber close to its margin. Its contacts are quite normal and show no disruption of the Ordovician rocks, while its metamorphic effects are negligible. The sediments on the northern side are not metamorphosed to any appreciable extent, while those on the southern side lie well within the metamorphic aureole of the granite.

The smaller bodies to the north-east of the main mass are undoubtedly connected with it in depth, and the abundance of inclusions of country rock in them suggests that they represent the 'leading end' of the intrusion. Smaller dykes occur nearer to the coarse granite, and in a number of cases appear to have been injected along minor shear faults in the batholithic roof, for there is noticeable drag in the sediments at their contacts. No evidence has been found to indicate the direction of inclination of these dykes.

The whole of the porphyrite series has been metamorphosed to a greater or less degree. As with the sediments, the higher grade metamorphic rocks usually occur nearest to a granite contact, but again there is a marked patchiness in the aureole. The course of metamorphism is practically the same as that described by Edwards (8) from the dacite-granodiorite contact at Warburton, but the textural stages recognized by him are not always distinguishable. Schistose rocks which are characteristic of the Warburton contact are not as well developed and are usually found close to contacts with either igneous or sedimentary rocks. The schistosity is a metamorphic effect and not caused by primary flow structures. The rocks undergoing metamorphism have been softened to a pasty condition in which small movements have sufficed to produce a well marked schistosity. In the metamorphosed agglomeratic rocks the inclusions have been drawn out into long streaks by this movement while small quartz veins cutting the rocks have undergone ptygmatic folding.

The nearest approach to the original unmetamorphosed porphyrite is a bluish-grey rock with a fine porphyritic texture showing small phenocrysts of felspar, up to 5 mm. across, and hypersthene set in an aphanitic base. In thin section it consists of a calcic andesine Ab_{50-60}, hypersthene, and rarely quartz, together with clots of secondary biotite, in a fine-grained groundmass of quartz, orthoclase and biotite, with larger crystals of plagioclase, ilmenite, apatite, zircon, and rarely pyrite.

The andesine phenocrysts are mostly rounded fracture fragments of larger crystals which are strongly zoned and twinned on the Carlsbad, albite, and pericline laws. They are often veined and coated with a thin film of oligoclase Ab_{80} (Pl. XI, fig. 4). The hypersthene is strongly pleochroic and sometimes contains minute inclusions of biotite and ilmenite. It is usually surrounded by rims of secondary biotite (X straw-yellow, Y, Z dark brown), associated coarser quartz, and rarely pale green hornblende (Pl. XI, fig. 3). Edwards (8) has noted these biotite rims even in unmetamorphosed hypersthene dacites caused by reaction between hypersthene and orthoclase. Larger biotite aggregates also surround ilmenite and pyrite grains (Pl. XII, fig. 1) and contain well formed apatite crystals. The groundmass biotite is also the pale yellow variety and is often chloritized, while occasional muscovite flakes are developed close to the andesine phenocrysts.

In a minor modification of the porphyrite primary biotite phenocrysts take the place of the hypersthene. These contain abundant iron ore dust and rutile needles and are surrounded by thin rims of pale secondary biotite and occasional muscovite flakes.

Contact Metamorphosed Hypersthene Porphyrite

Spotted Stage. The only difference to be seen in the hand specimen is the replacement of hypersthene by clots of biotite. In thin section the groundmass has become patchy and dirty through the presence of iron ore dust, while the plagioclase phenocrysts tend to aggregate, often with the biotite clots. Muscovite flakes are often present in these felspars, which are rather fractured and altered to a brown isotropic material, usually from the core outwards. Their composition is slightly more sodic Ab_{60-65}, while the rims and veins of oligoclase are wider. The hypersthene has been completely replaced by flakes and structureless clots of yellow to dark brown biotite with associated apatite and ilmenite crystals. Very small amounts of green hornblende may occur in these aggregates and in the straw zones surrounding them. Ragged primary biotite is also occasionally present, surrounded by secondary paler biotite flakes.

The groundmass is still fine-grained, but in some rocks intergrowths of quartz and felspar have developed. In one slide secondary biotite is a pale reddish-brown colour and the groundmass is coarser-grained. Pyrite has been introduced along fractures and cleavages and this increase in iron may account for the change in the biotite.

Stage 2. These rocks are a lighter grey colour, with a fine granular groundmass and a schistose or granoblastic texture. The schistose rocks occur near the edge of the dykes and their texture is caused by orientation of the biotite flakes. The plagioclase crystals are grouped together with associated granular quartz. They range from acid andesine Ab_{65} to oligoclase Ab_{75}, and the rims and veinlets of oligoclase Ab_{80} are wider and more numerous. The biotite aggregates are more scattered and individual flakes are larger and fewer in number. Green hornblende (X pale yellow-green, Y olive-green, Z deep-green), apatite, and sphene are associated with these clots, but ilmenite is almost absent. The groundmass is coarser-grained and consists of quartz, oligoclase, orthoclase and biotite. In some sections the groundmass is an intergrowth of quartz and felspar with scattered biotite.

Stage 3. The igneous texture of the porphyrites has now been completely obliterated, the products being fine-grained schistose or granoblastic rocks, containing porphyroblasts of jacketed plagioclase with cores varying from acid andesine Ab_{65} to basic oligoclase Ab_{70}. The surrounding rims of acid oligoclase Ab_{80} have sharp junctions with the cores, and contain small blebs of quartz and biotite. The biotite clots are composed of a few well-formed flakes of a more reddish variety (X pale-yellow, Y, Z dark reddish-brown). Large corroded pink garnets occur in a slide from near the granite contact at Hayes Hill. The granular groundmass consists of quartz, oligoclase, orthoclase and biotite, with accessory ilmenite, corroded apatite, zircon, and sometimes tourmaline and green hornblende.

Inclusions. Inclusions of altered shales and quartzites are abundant in the more agglomeratic porphyrites belonging to stages 2 and 3. In the schistose rocks the argillaceous inclusions have been drawn out into thin lenticles but the quartzite ones remain as small rounded pebbles. One inclusion has been offset along a fracture plane which has since healed during the metamorphism.

The shale inclusions have recrystallized to a fine-grained aggregate of quartz, orthoclase, oligoclase Ab_{72}, and red-brown biotite with accessory apatite and zircon, but no iron ore. In other inclusions flakes of pale green pinite are abundant. The quartzite inclusions consist of rounded and interlocking quartz grains with interstitial fine quartz, orthoclase, brown biotite, sericite, brown to blue tourmaline and waterworn zircon and apatite.

Granitized Rock. In the vicinity of a small outcrop of aplitic granite the schistose rocks have been granitized to a rather coarser-grained rock showing the introduction of orthoclase crystals up to 2 mm. long and smaller amounts of quartz, oligoclase Ab_{72}, and biotite. The andesine Ab_{60} cores of the original plagioclase are largely altered to a yellow isotropic material and the rims Ab_{70-75} are also rather dirty. The introduced orthoclase is sometimes perthitic and intergrown with quartz. Pink garnet is scattered through the rock with accessory apatite, zircon and iron ore.

MICROGRANODIORITE

The microgranodiorite outcrops as a small arcuate intrusion one mile long and up to a quarter of a mile wide and is a uniformly fine-grained rock with occasional phenocrysts of prismatic hornblende about half an inch long. Numerous veins of medium-grained granite traverse the microgranodiorite, often along joint planes, and towards the western end of the intrusion almost completely replace it. Xenoliths are uncommon in the microgranodiorite.

In thin section it contains abundant zoned plagioclase Ab_{55-85} and biotite, with lesser amounts of orthoclase, quartz and green hornblende, and accessory iron ore, zircon, apatite, sphene and orthite. Small blebs of myrmekite occur interstitially, while orthoclase perthite is rarely present as large poikiliths containing hornblende, biotite and abundant apatite needles. Hornblende is subordinate to biotite and often crystallizes second. Rare aggregates of a colourless fibrous amphibole are secondary after an earlier mineral, possibly a pyroxene.

GRANODIORITE

The granodiorite is a medium-grained equigranular grey rock consisting of quartz, zoned andesine-oligoclase Ab_{65-80}, orthoclase microperthite, biotite and small amounts of corroded hornblende, with accessory apatite, iron ore, zircon and sphene. Microperthite is the last major constituent to crystallize and the perthite lamellae take the form of fine parallel threads and thin veins. Where plagioclase and orthoclase are in contact a rim of acid oligoclase Ab_{89} containing fine myrmekitic quartz has formed within the plagioclase crystal and the quartz is oriented across this rim.

GRANITE

The main granite is a rather coarse-grained grey rock consisting of tabular orthoclase microperthite crystals up to an inch long, quartz, zoned oligoclase Ab_{75-85}, biotite, and occasional muscovite flakes, with accessory iron ore, apatite, and zircon. The perthite crystals have ragged margins, having crystallized later than the other minerals, and are characteristically twinned on the Carlsbad law. The perthite lamellae are predominantly of the vein type but occasionally fine exsolution threads are present. The vein lamellae are acid oligoclase Ab_{80-85} and show fine albite twinning. Crystals of oligoclase included in the perthite are jacketed with thin rims of exsolved acid oligoclase Ab_{85} of the same composition as the surrounding vein lamellae, and where they are optically parallel to the perthite the twin lamellae of the plagioclase project into the host and grade into the normal exsolution veins. The cores of the oligoclase crystals also contain blebs of orthoclase in optical continuity, with the host forming a replacement antiperthite.

The granite dyke and associated veins and apophyses are finer-grained than the main intrusion, but are similar mineralogically, with rather less biotite and the addition of pink garnet in small pools intergrown with quartz. Tabular perthite crystals are absent, so that no flow structures are apparent.

QUARTZ DIORITES

Two distinct types of quartz diorite have been found in the area, one a fine-grained hornblendic rock associated with the hypersthene porphyrites and the other a medium-grained rock possibly derived from the granite magma by contamination. The first occurs in a small pocket on the edge of a mass of porphyrite and consists of quartz, andesine-oligoclase Ab_{60-75}, hornblende, and chloritized biotite, with accessory iron ore, apatite, sphene, and calcite. Some hornblende clots contain cores of a corroded colourless pyroxene with a high extinction angle, possibly diopside.

The second dioritic mass is a small isolated apophysis in the Ordovician hornfelses surrounded by a zone of diopside-bearing rocks. It is a medium-grained granitic rock containing quartz. andesine Ab_{53}, orthoclase, biotite and hornblende, with accessory magnetite, apatite and zircon. It is obviously related to the granitic rocks and its high heavy mineral index (34·8) suggests that it is the product of contamination by fairly basic rocks.

QUARTZ PORPHYRIES

The northerly trending dykes in the Ordovician rocks are quartz porphyries with variable textures. The most important occur outside the area to the west near Baynton, where one dyke is at least five miles long. The porphyritic types contain phenocrysts of quartz, orthoclase, and rarely oligoclase Ab_{85} in a base of the same minerals, biotite and sericite. The fine-grained rocks approach aplites in texture but are similar mineralogically to the porphyries.

APLITES

Small dykes and veins of aplite are found throughout the 'fracture zone' and occasionally along the contact of the main granite. They contain quartz, abundant orthoclase and orthoclase microperthite, less oligoclase Ab_{70-75}, muscovite and biotite. Quartz-garnet pools may be present, associated with green biotite. Biotite is scarce and usually a green variety, while muscovite is both primary and secondary after orthoclase.

PEGMATITES

Pegmatitic veins are not at all common and are not particularly coarse rocks, the felspars being about one inch long. They are composed of graphic intergrowths of quartz and orthoclase perthite, subordinate oligoclase Ab_{75}, and small amounts of biotite, tourmaline and apatite.

PETROGENESIS

On the field evidence available there appears to be no reason to doubt the view that the granitic rocks have originated by direct crystallization of fluid magma intruded from below by the recognized processes of stoping and perhaps cauldron subsidence. This is in agreement with the widely accepted theories of origin of the small high-level granitic intrusions and is supported by the conclusions arrived at by workers on other Central Victorian granites. In many of these intrusions, e.g., Mt. Macedon, Dandenong Ranges, Marysville, partial collapse of the batholithic roof has allowed large volumes of magma to be extruded at the surface, consolidating as hypersthene dacites.

The contact of the Cobaw granite is a typical transgressive one with normal contact metamorphic rocks occurring right up to the junction. The effects of granitization have been noted only in isolated localities and are then on a very small scale. The presence of a granite rim with few inclusions between the country rock and the granodiorite, containing relatively abundant inclusions, is also evidence against any theory of granitization by which xenoliths would be more common nearer to the contacts of the intrusion. As stated above, the granite has apparently been intruded around the granodiorite as a ring intrusion soon after the consolidation of the latter. The gradational zone between the two is explained by the introduction of material from the granite magma into the granodiorite.

The abundance of ramifying granitic veins in parts of the 'fracture zone' are indicative of a fluid magma and the occurrence of a sedimentary zenolith in one of these veins, itself intruding microgranodiorite, is certainly only explicable in terms of a fluid magma.

The origin and composition of the parent magma is quite outside the scope of this paper, while the field evidence, which indicates the normal trend towards increased acidity, is insufficient to determine the relative importance of the processes of differentiation and assimilation in the derivation of the various rock types.

Xenoliths

Xenoliths are numerous and widely distributed throughout the granodiorite but, as mentioned above, are uncommon in the granite. They are usually less than one foot across, but larger blocks have been observed. All stages in the normal sequence of basification and felspathization can be recognized, particularly in the coarse granite, where the xenoliths consist of a dark core surrounded by a wide felspathic strew zone.

Xenoliths in the medium-grained granite have suffered little alteration and are very similar to the rocks of the metamorphic aureole. However, those in the coarse granite and granodiorite which have been acted on by the magma for a longer time, probably at a higher temperature, have been completely reconstituted through recrystallization and interchange of material with the magma.

Three distinct groups can be recognized according to their mineralogical composition:

1. Types rich in alumina derived from the sedimentary hornfelses;

2. Quartz-plagioclase-biotite rocks derived from the porphyrites; and
3. Hornblende-bearing types of no proven origin.

The less altered xenoliths of group 1 are very similar to the Ordovician cordierite hornfelses, but the cordierite has altered to pinite and oligoclase Ab_{70-75} has been introduced. With further recrystallization, silica and potash are removed by the magma and minerals rich in alumina, such as corundum, spinel and sillimanite, appear. Cordierite occurs as tabular poikiloblasts including these minerals and often showing later alteration to pinite. The other minerals present are quartz, reddish-brown biotite and oligoclase. One such basified rock is cut by a vein of orthoclase with small amounts of quartz, chlorite, sphene and calcite.

Xenoliths belonging to group 2 are rare and confined to the granite. They are characterized by the occurrence of jacketed andesine Ab_{65-70} and clots of ragged biotite, and the absence of hornblende. The other minerals are quartz, subordinate orthoclase, ilmenite, apatite and zircon. Many of the biotite flakes are deformed and some andesine crystals have been granulated and inshot with fine quartz. The texture and mineralogy of these inclusions strongly supports their derivation from the metamorphosed hypersthene porphyrites.

The great majority of the inclusions belong to group 3 and are fairly basic lime-rich felspathized types characterized by an abundance of hornblende and to a lesser extent diopside. Those in the granodiorite have been well granitized and consist of quartz, andesine-oligoclase Ab_{65-70}, green hornblende, biotite, diopside, apatite needles, zircon, sphene and rare iron ore. Quartz is usually last to crystallize, but one slide shows large orthoclase porphyroblasts enclosing the other minerals. An inclusion from the granite has a strew zone of similar composition surrounding a core of plagioclase, quartz, and biotite, with large poikiloblasts of albite perthite Ab_{98} containing small resorbed grains of biotite, diopside and iron ore. Inclusions of this class showing little or no alteration have not been found, so their origin cannot be determined with any certainty. They may, however, be derived from the Cambrian igneous rocks.

Diopside-bearing Rocks

An association of massive diopside-bearing rocks occurs within the metamorphic aureole as thin lenticular bodies outcropping along the boundaries of the various rock types, usually between the Ordovician hornfelses and one of the igneous rocks. They are fine-grained white rocks composed essentially of quartz, diopside and labradorite, in varying proportions, with or without green hornblende, wollastonite, ?prehnite, iron ore, sphene and apatite. A dark green variant contains hornblende in excess of diopside, due probably to the local concentration of solutions.

The textures of these rocks are definitely metamorphic and vary from fine-grained granular rocks to coarser crystalline types in which interpenetration of the minerals is a common feature. The finer-grained rocks contain fine granular diopside in a base of quartz, plagioclase and iron ore (Pl. XII, fig. 3), but in some cases coarser-grained quartz is present with interstitial diopside and plagioclase. One such rock at a junction with hornfels provides the only evidence available of the origin of the suite. The unaltered hornfels consists of strained quartz in a base of biotite, cordierite and iron ore. Across the junction biotite becomes replaced first by actinolite and then diopside, plagioclase enters, cordierite is largely altered and sphene replaces ilmenite. The quartz grains become more scattered but are quite unchanged.

The coarser rocks are more variable in composition. Labradorite and diopside are coarser, but quartz is still unaltered. One rock contains wollastonite (X = 1·621, Y = 1·628, Z = 1·631) and another a mineral agreeing optically with the ?prehnite described by Tattam (27) from the metamorphic aureole of the Bulla granodiorite, and showing traces of the bow-tie structure typical of prehnite. The same rock contains an unidentified pinkish mineral of low refractive index (below balsam) with numerous needle-like inclusions.

Quartz is less common in the hornblendic rocks and has recrystallized, often intergrown with the labradorite. Hornblende is a pale green variety containing numerous pleochroic haloes surrounding minute inclusions. Fibres of pale orange-brown biotite are very rare.

The origin of these rocks is open to much speculation, which is not helped by the poor field occurrences. Tattam has described similar rocks from Bulla occurring as lenses within the cordierite hornfelses and thought by him to be metamorphosed calcareous concretions. In the present case the diopsidic rocks transect the bedding of the hornfelses and are therefore not simply metamorphosed sediments. Their textures and mineral assemblages are against their being igneous rocks. They are thought to be derived through metasomatism of the hornfelses by lime-rich solutions, which is supported by the slide showing a contact between the two rocks. The fact that some outcrops lie between two igneous masses is not incompatible with this view because small screens of hornfels are often present along these contacts. Cordierite and biotite have been replaced by lime-bearing minerals, diopside, labradorite and hornblende. Ilmenite has altered to sphene. With further introduction of lime, wollastonite and ?prehnite have developed. The source of the lime-rich solutions is unfortunately not indicated by the evidence available.

The Metamorphic Aureole

The rocks of the metamorphic aureole of the Cobaw granite have been described above under the corresponding source rocks and it is appropriate at this stage to discuss briefly the general features of the aureole.

The metamorphic aureole is not particularly wide, except in the 'fracture zone', where its width is due to the intimate association of the hornfelses and igneous rocks. Outside the 'fracture zone' the intensity of metamorphism does not appear to have been great, since cordierite hornfelses are found only as a thin zone right at the granite contact. The most important factor in the metamorphism therefore appears to have been not the actual temperature, which was not high, but the duration of the heating. In the 'fracture zone' the long and complex intrusive history has allowed ample time for the metamorphic reactions to proceed to completion. The occurrence of minerals such as corundum and spinel in xenoliths is due to the removal of silica by the magma and not to the temperature of the intrusion.

The effects of pressure have been negligible but account for slight ptygmatic folding of some cordierite hornfelses and the schistosity of the metamorphosed porphyrites.

The composition of the original rocks has played a large role in their behaviour during metamorphism. Thus the Cambrian rocks and the hypersthene porphyrite, consisting of more reactive materials, show visible alteration long before the more stable sedimentary rocks. The role of volatiles, particularly water, is also important in promoting reaction among the minerals, and the marked patchiness of the aureole may be due in part to the local concentration of aqueous solutions.

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Description of Plates

PLATE X

Fig. 1.—Altered tuff containing pseudomorphs of talc after ferromagnesian minerals in a base of fine-grained talc. (6967 ×50.)
Fig. 2.—Altered lava showing skeletal actinolite and a veinlet of secondary quartz. (6968 ×50.)
Fig. 3.—Albite-rich rock showing crystals of clinozoisite (high relief) and quartz (clear), and fine-grained quartz-albite intergrowths (speckled grey). (6955 ×50.)
Fig. 4.—Phenocryst of twinned albite in a groundmass of albite and stilpnomelane. (6945 ×27.)

PLATE XI

Fig. 1.—Fibres of stilpnomelane in a cherty base. (6963 ×50.)
Fig. 2.—Tremolite hornfels showing needles of tremolite partially replacing a crystal of quartz. (6964 ×140.)
Fig. 3.—Metamorphosed hypersthene porphyrite showing hypersthene and ilmenite crystals being replaced by flakes of biotite. (6970 ×50.)
Fig. 4.—Crystal of andesine jacketed by oligoclase in metamorphosed hypersthene porphyrite. (6973 ×50.)

PLATE XII

Fig. 1.—Rim of biotite flakes surrounding a grain of ilmenite in metamorphosed hypersthene porphyrite. (6972 ×110.)
Fig. 2.—Quartz-biotite-cordierite hornfels containing porphyroblasts of quartz and andesine. (6969 ×50.)
Fig. 3.—Fine-grained diopside-bearing rock composed of quartz, diopside and an unidentified pink mineral. (6971 ×50.)